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Design principles for plasmonic thin film GaAs solar cells with high absorption enhancement

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In this paper, a systematic design and analysis of gallium arsenide thin film solar cells incorporated with a periodic silver nanoparticles (NPs) structure to enhance light absorption is presented using the finite element method. The influence of the silver nanoparticles diameter and structure periodicity on light absorption has been examined. It is found that the absorption is significantly enhanced due to the surface plasmon induced by the silver nanoparticles. The optimal structural parameters are achieved when the diameter of the nanoparticles is 200 nm and the periodicity is 444 nm. This gives rise to a maximum ultimate photocurrent of 26.32 mA/cm² under AM1.5G solar irradiation. In addition, the underlying physics that accounts for the enhancement is discussed. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4749800>]

I. INTRODUCTION

High efficiency solar cells require optically thick layers to absorb sunlight completely.¹ However, such extensive usage of material has substantially contributed to its cost. Alternative thin film cells have been developed to address this issue,^{2,3} which unfortunately suffers from a drop in light absorption.¹ Nanostructure array based thin film solar cells have been proposed to increase the light absorption due to their excellent anti-reflective property.^{4,5} However, the large surface areas of the nanostructure arrays increase minority carrier recombination at the surface and junction regions, which seriously degrades the efficiency of the solar cells.⁶ In addition, it remains a challenge to fabricate those ordered periodic nanostructures using a low cost method.

Recently, an attractive method of incorporating metal plasmonic nanoparticles (NPs) in photovoltaic devices has demonstrated the ability to solve the problem of light trapping for thin film solar cells, while keeping the surface area unchanged.^{7–10} By a proper design of the size, shape, and dielectric environment of the metal NPs, it is possible to guide and manage the incident sunlight due to the collective oscillations of electrons at the surface of the metal NPs.^{11–14} The enhanced light absorption is mainly attributed to the increased optical path of incident light,^{15,16} intensified electric-field,¹⁷ and enhanced forward scattering.^{18,19} Broadband enhancement of light absorption has been achieved with 43% improvement in short circuit current by using the plasmonic metal structures for silicon based cells.²⁰ Hence, it is a promising method to increase the light absorption while reducing the recombination loss, and achieves higher conversion efficiency for thin film solar cells.

Although much effort has been focused on silicon based solar cells, gallium arsenide (GaAs) has been demonstrated

to be a better material to achieve higher efficiency due to its high absorption coefficient and ideal bandgap.^{21,22} So far, there is no systematic research performed for GaAs thin film solar cells to investigate the optimum metal NP parameters that will give rise to maximum light absorption. In this paper, we present a study on the light absorption enhancement for GaAs thin film solar cells by incorporating silver (Ag) nanospheres (NSs). The effects of Ag NSs diameter (D) and the structure periodicity (P) on light absorption enhancement are investigated to understand the fundamental design principles for Ag enhanced light absorption in GaAs thin film solar cells. Our result indicates that the light absorption in GaAs thin film solar cells can be substantially changed by modifying the D and P. It is found that absorption is significantly improved when D is 200 nm and P is 444 nm. It achieves an absorption enhancement of ~31% compared with GaAs planar thin film cells. The physics behind the observation is discussed in this work.

II. SIMULATION METHODOLOGY

Figure 1(a) shows the schematic of the GaAs thin film structure simulated in this study using the finite element method.²³ The height H of the GaAs thin film is fixed as 2 μm. The D and P of the Ag NSs are varied to find the optimal structural parameters. Monochromatic plane wave is normally incident onto the structure with perfectly matched layer boundary conditions. The wavelength (λ) range of the incident light is from 300 nm to 870 nm, covering the main part of solar spectrum of interest. The interaction between the incident light and the nanostructure is realized by infinitely extending the unit square cell (Fig. 1(a)) in two dimensions using the periodic boundary condition which can account for the multiple scattering effects. The simulation is performed using the commercial software, high frequency structure simulator (HFSS). It employs the adaptive meshing

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FIG. 1. (a) Schematics of the GaAs thin film structure with the Ag nanospheres on the top surface. (b) Reflectance, (c) transmittance, and (d) absorption spectra of GaAs thin film and absorption spectra of Ag NS with a fixed D/P ratio of 0.5. The $2\ \mu\text{m}$ thick film (no Ag on top) serves as the reference.

which is automatically tuned to obtain the most accurate and efficient mesh possible. The optical absorption is obtained by solving the Maxwell's equation arising from the interaction between the incident light and the GaAs thin film structure. Therefore, the spatial distribution of the energy flux can be obtained. Hence, by integrating the solved electromagnetic field, the reflectance (R), transmittance (T), and absorption in GaAs (A_{GaAs}) and Ag NSs (A_{Ag}) can be calculated.

The optical constants of GaAs and Ag are taken from the literature.²⁴

III. RESULTS AND DISCUSSION

Figures 1(b) and 1(c) depict the reflectance (R) and transmittance (T) spectra, respectively, for the GaAs thin film with different D (40 nm, 120 nm, 200 nm, 280 nm, and 320 nm)

and a fixed D/P ratio of 0.5. The corresponding results for a planar 2 μm thin film without Ag NSs are also plotted for comparison. Fig. 1(b) shows that the reflectance is reduced for different D compared to the planar cell, especially for D of 200 nm because the Ag NSs can effectively scatter the incident light and couple it into the underlying layer.^{7,19} The transmittance ($R + T + A_{\text{GaAs}} + A_{\text{Ag}} = 100\%$) shown in Fig. 1(c) for the planar cell and the other cells incorporated with Ag NSs is small, indicating that most of the incident light is absorbed before reaching the bottom of the structure.

Figs. 1(d) and 1(e) show the absorption spectra of the GaAs film (A_{GaAs}) and Ag NSs (A_{Ag}), respectively. It is well known that as D of Ag NSs increases, the dipolar mode resonance is red shifted and broadened, and higher order modes are also excited.^{11,19} At D = 200 nm, the resonance wavelength of the dipolar mode shifts towards the visible light region with a much enhanced forward scattering (σ_s),¹¹ contributing to the substantial absorption improvement in the GaAs film. Meanwhile, the excited higher order modes located in the short wavelength region (360 nm, 450 nm), indicating absorption loss in Ag NSs, accounts for the drops in absorption in the GaAs film for λ below 500 nm. Therefore, at D = 200 nm, the absorption enhancements in the GaAs film and absorption loss in Ag NSs occur at different regions of the solar spectrum,¹¹ which is advantageous in improving the light absorption for GaAs film.

As D is reduced to 40 nm, only a marginal improvement in absorption is observed for λ above 400 nm compared to the planar GaAs film. However, the performance for light below 400 nm degrades even though less light is reflected (Fig. 1(b)). Mainly, the dipolar mode is excited within the NSs,¹¹ which has a much higher absorption cross section area (σ_a) than the scattering cross section area (σ_s). Hence, a strong absorption in Ag NSs occurs around the resonance wavelength (~ 360 nm, corresponding to peak in the absorption spectra of Ag NSs), causing the absorption reduction in GaAs film. However, as D is increased to 320 nm, the absorption is degraded with a substantial increase in reflection compared with that D = 200 nm. This is because although the larger Ag NSs offer better scattering ability, the percentage of the light scattered into the underlying thin film decreases,¹⁴ leading to a drop in the absorption. Therefore, by considering the tradeoff between enhanced scattering and reduced percentage of light scattered into underlying layer, the optimal D can be determined.

Figure 2 shows the optical characteristics of the GaAs thin film with different D/P ratios (0.2, 0.5, and 0.8) at a fixed D of 200 nm. At D/P of 0.8, the absorption drops substantially over the whole spectrum compared to that of planar film. At this high density of surface coverage, light reflection increases due to the strong backward scattering.¹⁹ As D/P ratio decreases to 0.5, the reflection is reduced and the absorption is enhanced compared with the planar GaAs film. The

FIG. 2. (a) Absorption and (b) reflectance spectra of GaAs thin film with a fixed D of 200 nm.

FIG. 3. (a) Short-circuit current density of GaAs thin film at different D as a function of the D/P ratio and (b) optimized short-circuit current density at different D.

FIG. 4. (a) Absorption spectra and (b) Short-circuit current density of GaAs thin film for different film heights.

absorption is maintained above 80% for long wavelength light. When the D/P ratio is further reduced to 0.2, small enhancement of the absorption is observed due to the slightly reduced reflectance compared to the planar film with negligible absorption in the Ag NSs. At this small D/P ratio, the Ag NSs can be considered as isolated from each other, and hence the interaction between the Ag NSs is weak and the effect of collective modes of Ag NSs is reduced.⁷ Hence, their contribution to light absorption in GaAs film is marginal.

In order to determine the optimized geometric configuration, the short circuit current density (J_{sc})^{25,26} is calculated to facilitate the performance comparison by assuming that the internal quantum efficiency is 1

$$J_{sc} = \frac{q}{hc} \int_{300}^{870} \lambda P(\lambda) A(\lambda) d\lambda.$$

In the above equation, q is the electronic charge, h the Planck's constant, λ the wavelength of sunlight, $A(\lambda)$ the absorption efficiency, and $P(\lambda)$ the spectral irradiance of the standard AM1.5G solar spectrum. Figure 3(a) shows the J_{sc} for different D of Ag NSs incorporated GaAs thin film as a function of the D/P ratio (only J_{sc} larger than that of planar

film of 20.09 mA/cm² is shown). From Fig. 3(a), it is seen that J_{sc} generally increases and then decreases with the D/P ratio for a given D. Fig. 3(b) shows the optimized J_{sc} for each Ag NSs diameter. At small D = 40 nm, the enhancement in J_{sc} compared to the planar cell is small. The J_{sc} increases to its peak value of 26.32 mA/cm² at D = 200 nm, implying that the optimized geometry can absorb ~81% of the above-band-gap sunlight.²⁶ A further increase in D beyond 200 nm results in a drop in J_{sc} from the optimal value.

Figure 4 shows the absorption spectra and J_{sc} for the GaAs solar cells at different film thicknesses with the optimized structural parameters obtained above. As H reduces from 2 μ m to 400 nm, the absorption remains unchanged for short wavelength light but decreases for longer wavelength light due to insufficient thickness for light absorption. Besides, compared with the film without the Ag NS, J_{sc} is consistently higher by having the Ag NS.

IV. CONCLUSIONS

In summary, simulation was used to design efficient GaAs thin film solar cell by incorporating Ag NS array on the top surface. The effect of physical parameters of the

nanoparticle array on the absorption efficiency of GaAs thin film is investigated. It is found that an optimized geometry design with a periodicity of 444 nm and diameter of 200 nm for the AG NS array would absorb 81% of the above-band-gap sunlight, achieving a short circuit current of 26.32 mA/cm². It demonstrates a 31% improvement in short circuit current compared with the planar film.

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